Chapter 20 NUCLEAR PHYSICS

- Nuclear physics is the field of physics that studies atomic nuclei and their constituents and interactions.

Atomic Nucleus

- ***Etymology:***
  The term nucleus is from the Latin word nucleus, a diminutive of nux ("nut"), meaning the kernel (i.e., the "small nut") inside a watery type of fruit (like a peach).
  In 1844, Michael Faraday used the term to refer to the "central point of an atom". The modern atomic meaning was proposed by Ernest Rutherford in 1912. The adoption of the term "nucleus" to atomic theory, however, was not immediate. In 1916, for example, Gilbert N. Lewis stated, in his famous article The Atom and the Molecule, that "the atom is composed of the kernel and an outer atom or shell"
- ***Constituents:*** Proton and neutron.
- ***Discovery:***
  Nucleus for the first time was discovered by Rutherford and his colleagues in 1911 through his alpha scattering experiment.
  Proton was discovered by Goldstein.
  Neutron was discovered by James Chadwick.
- ***Charge on Nucleus:***
  All nuclei contain protons and neutrons except ordinary hydrogen atom which has only single proton.
  Proton has charge +e and neutron are neutral.
  The overall charge on nucleus is positive.
- ***Nuclide:***
  A single nuclear specie having specific value of Z and N is called Nuclide.
- ***Mass of the nucleus:*** 99.9% Mass of an atom is due to nucleus.
  Mass no. of nuclei $(A) = Z + N$
  Where Z = no. of protons in the nucleus; N = no. of neutrons.
  Symbolically atomic nuclei are represented as X_Z^A
  The mass of proton is 1836 times heavier than that of electron.
  The mass of neutron is 1840 times heavier than that of electron. That's why the whole mass of an atom is considered to be enclosed in nucleus.
- ***Representation:***

$$X_Z^A$$

WHERE

X = symbol of atom
Z = Atomic number = Number of protons
A = Atomic mass number
= total number of nucleons
= number of proton + Neutron

- ***Nucleon:***
  Collectively neutron and proton are called nucleon.

In an Atom:

No of electron in a nucleus = Number of protons in a nucleus	Number of protons = Atomic number	Number of neutrons = Mass number − Atomic number

Atomic number of the element

= Serial number of the element in periodic table
= Charge on the nucleus of the atom of the element
= Number of protons present in the nucleus of the atom of the element
= Number of extranuclear electrons present in the atom of the element

Atomic Mass

⇒ An atomic mass is defined as the total mass of electron, proton and neutron in atom.

⇒ Atomic masses are conventionally expressed in atomic mass units.

⇒ *Atomic mass unit:*

It is defined as $\frac{1}{12^{th}}$ the mass of carbon atom (at rest and in ground state), it is abbreviated as 'amu' and often denoted as u.

Carbon is monoatomic therefore there are 6.02×10^{23} atoms of carbon. These have a mass of 12 g.

$$\therefore \text{Mass of one atom of carbon atom} = \frac{12}{6.02 \times 10^{23}} g = \frac{12}{6.02 \times 10^{26}} kg$$

$$\therefore 1\ amu = \frac{1}{12} \times \frac{12}{6.02 \times 10^{26}} kg \Rightarrow 1.66 \times 10^{-27} kg$$

⇒ *Equivalence energy of unified mass:*

It is expressed by using Einstein equation:

$$E = mc^2 \Rightarrow (1.66 \times 10^{-27} kg)(3 \times 10^8)^2 \Rightarrow 1.49 \times 10^{-10} J$$

Mass of electron	Mass of proton	Mass of neutron
$= 9.1 \times 10^{-31} kg$ $= 0.000548\ amu$ $= 0.51\ MeV$	$= 1.672 \times 10^{-27} kg$ $= 1.00727\ amu$ $= 937\ MeV$	$= 1.675 \times 10^{-27} kg$ $= 1.00865\ amu$ $= 938\ MeV$

⇒ *For interconversion:*

Between Joule and U	Between Kg and U
$1J = \frac{1}{1.49 \times 10^{-10} U}$	$n(1U) = n(1.66 \times 10^{-27})$

Isotopes, Isobars, Isotones, Isomers, Isoters and isodiapheres

	Characteristics⇒ Z =atomic no, A =mass no, N= neutrons, P = Protons	Examples
Isotopes	Z = same, A = different	H_1^1, H_1^2, H_1^3, $U_{92}^{235}, U_{92}^{238}$
Isobars	Z = different, A = same	$Ra_{88}^{228}, Th_{90}^{228}$
Isotones	N = same, nucleons = different, Z = different	Ar_{18}^{39}, K_{19}^{41}
Isomers	N same, P = same, Z = same, A = same Nuclear energy levels = different	$U-X_2, U-Z$
Isoters	No. of atoms = same, no of electrons = same Physical properties = same	CO_2, N_2O
Isodiapheres	Isotopic excess means $(N-P)$ = same	$U_{92}^{235}, {}_{90}Th^{231}$

Mass Spectrograph

⇒ Mass spectrometer or spectrograph is a device used to measure mass, separate isotopes of an elements and ratio of isotopes of an element is called mass spectrograph.

⇒ It is an analytical technique that ionizes chemical species and sorts the ions based on their mass-to-charge ratio.

⇒ An atom is placed and ionizes inside it therefore.

"The working principle of mass spectrometer is based on Deflection of ions in uniform magnetic field"

⇒ *Main parts:*

1) Potential source: source which is used to accelerate ion toward chamber.
2) Furnace: used to ionize atom.
3) Metal chamber: it is arrangement throughout which a uniform magnetic field is applied.
4) Detector: Used to detect the path of atom.

⇒ *Steps involved:*

1) **Ionization:** (The atom or molecule is ionized by knocking one or more electrons off to give a positive ion. This is true even for things which you would normally expect to form negative ions (chlorine, for example) or never form ions at all (argon, for example). Most mass spectrometers work with positive ions).
2) **Acceleration:** (The ions are accelerated so that they all have the same kinetic energy).
3) **Deflection:** (The ions are then deflected by a magnetic field according to their masses. The lighter they are, the more they are deflected).
4) **Detection:** (The beam of ions passing through the machine is detected electrically).

The amount of deflection also depends on the number of positive charges on the ion - in other words, on how many electrons were knocked off in the first stage. The more the ion is charged, the more it gets deflected.

MCQ: In mass spectrometer used for measuring the masses of ions, the ions are initially accelerated by an electric potential V and then made to describe semicircular path of radius R using magnetic field B. If V and B are kept constant, the ratio charge/ mass will be proportional to

a) $1/R^2$ b) R^2 c) R d) 1/R

In mass spectrometer, when ions are accelerated through potential V

$$½(mv^2) = qV \rightarrow eq(1)$$

As the magnetic field curves the path of the ions in a semicircular orbit

$$Bqv = mv^2/R$$

$v = BqR/m$ —eq(2) Substituting value of eq(2) in eq(1)

$$\frac{1}{2}m\left[\frac{BqR}{m}\right]^2 = qV = \frac{q}{m} = \frac{2V}{B^2R^2}$$

since V and B are constants, $\frac{q}{m} \propto \frac{1}{R^2}$

Answer: (a)

Mass defect (کمی)

⇒ It has been observed that actual mass of the nucleus (determined by mass spectrometer of high resolving power) is always less than the sum of masses of proton and neutrons in Free State.

⇒ This difference in masses is called mass defect.

⇒ It is given by:

$$\Delta m = [Zm_p(A - Z)m_n] - M_{nucleus}$$

$$m_p \rightarrow Mass\ of\ proton, m_n \rightarrow Mass\ of\ neutron, M_{nucleus} \rightarrow Mass\ of\ nucleus$$

$$Z = atomic\ number, A = Mass\ number$$

Conceptual

It has been observed that there is a difference between expected mass and actual mass of a nucleus.

$$M_{expected} = Zm_p + (A - Z)m_n$$
$$M_{observed} = M_{atom} - Zm_e$$

It is found that:

$$M_{observed} < M_{expected}$$

Hence, mass defect is defined as:

$$Mass\ defect = M_{expected} - M_{observed}$$
$$\Delta m = [Zm_p(A - Z)m_n] - [M_{atom} - Zm_e]$$

Binding energy

⇒ It is defined as energy released during formation nucleus as a result of disappearance of mass i.e., mass defect.

⇒ The neutrons and protons in a stable nucleus are held together by nuclear forces and energy is needed to pull them infinitely apart (or the same energy is released during the formation of the nucleus. This energy is called the binding energy of the nucleus.

⇒ If Δm is mass defect then according to Einstein's mass energy relation

Binding energy in joule (this happened when mass defect is in kg):

$$\text{Binding energy} = (\Delta m)c^2 = ([Zm_p + (A-Z)m_n] - M_{nucleus})c^2$$

⇒ Binding energy in MeV (it happened when mass defect is expressed in amu):

$$\text{Binding energy} = \Delta m \times 931\ MeV$$

⇒ **Binding energy per nucleon**: The average energy required to release a nucleon from the nucleus is called binding energy per nucleon.

$$\text{Binding energy per nucleon} = \frac{\text{Total binding energy}}{\text{Mass number (total nucleons)}} = \frac{\Delta m \times 931}{A} \frac{MeV}{Nucleon}$$

⇒ Binding energy per nucleon ∝ Stability of nucleus

Mass number	Binding energy per nucleon
$A < 20$	A nucleus with this type of mass number have greater B.E per nucleon then their neighbors.
$A = 56$	The binding energy per nucleon is maximum for nuclei for this mass number. Its value is 8.8 MeV per nucleon.
$A > 56$	binding energy per nucleon gradually decreases for uranium ($A = 238$), the value of binding energy per nucleon drops to 7.5 MeV

The energy differences in allowed energy levels of a nucleus are generally large of the order of MeVs. Hence, it is difficult to excite the nucleus by usual method of supplying energy as heat.

Radioactivity

⇒ Radioactivity is a process in which nucleus of certain Element undergo spontaneous disintegration without excitation by Any external means.

⇒ It is exhibited by atoms with A>192 and Z>82. It was discovered by Henry Becquerel. Lead isotope is the stable end product of any natural radioactive series Radio activity is a nuclear process and not an atomic process.

⇒ All heavy elements from bismuth through uranium and a few of lighter elements have naturally occurring isotopes which possess the property of radioactivity.

⇒ These isotopes have unstable nuclei and attain stability through the phenomenon of radioactivity. The activity results in the emission of a complex type of powerful radiations, known as alpha, beta and gamma rays.

⇒ All those substances which have the tendency to emit these radiations are termed radioactive materials.

⇒ The property of disintegration of a radioactive material is independent of temperature, pressure and other external conditions.

⇒ Radioactivity is a nuclear phenomenon, i.e., the kind of intensity of the radiation emitted by any radioactive substance is absolutely the same whether the element is present as such or in any one of its compounds.

⇒ The phenomenon of radioactivity does not depend on the orbital electrons but depends only on the composition of nucleus.

⇒ During nuclear changes all conservation laws are obeyed. (i.e. Law of conservation of No of nucleons)

⇒ A radioactive material can emit three types of rays:

1) α (alpha)
2) β (Beta)
3) γ (gamma)

1) Alpha decay:

When an α-particle $[^4_2He]$ is emitted from the nucleus of an atom of the parent element, the nucleus of the new element, called daughter element, possesses atomic mass or atomic mass number less by four units and nuclear charge of atomic number less by 2 units because α −particle has mass of 4 units and nuclear charge of two units.

Note that Weak nuclear forces are responsible for $\alpha - decay$.

Alpha decay is possible whenever the mass of the original neutral atom is greater than the sum of the masses of the final neutral atom and the neutral helium atom.

$$\text{Parent element} \xrightarrow{-\alpha} \text{Daughter element}$$

	Parent element	Daughter element
Atomic mass:	A	$A-4$
Atomic number:	Z	$Z-2$

For example: in the following transformations, each α-particle, emission is accompanied by decrease of atomic mass by 4 and of atomic number by 2.

$$Ra^{226}_{88}\,_{Radium} \xrightarrow{-\alpha} Rn^{222}_{86}\,_{Radon} + He^{4}_{2}$$

$$U^{238}_{92}\,_{Uranium} \xrightarrow{-\alpha} Th^{234}_{90}\,_{Thorium} + He^{4}_{2}$$

2) Beta Decay:

- ✓ β-particle is merely an electron which has negligible mass. Whenever a beta particle is emitted from the nucleus of a radioactive atom, the nucleus of the new element formed possesses the same atomic mass but nuclear charge or atomic number is increased by 1 unit over the parent element.
- ✓ Beta particle emission is due to the result of decay of neutron into proton and electron.

$$n^{1}_{0} \longrightarrow p^{1}_{1} + e^{0}_{-1}$$

The electron produced escapes as a beta particle leaving proton in the nucleus.
If the antineutrino is not produced then law of conservation of momentum is not obeyed.

$$\text{Parent element} \xrightarrow{-\beta} \text{Daughter element}$$

	Parent element	Daughter element
Atomic mass:	A	A
Atomic number:	Z	$Z+1$

For example:

$$Pb^{214}_{82}\,_{Lead} \longrightarrow Bi^{214}_{83}\,_{Bismuth} + e^{0}_{-1}$$

$$Th^{234}_{90}\,_{Thorium} \longrightarrow Pa^{234}_{91}\,_{protoactinium} + e^{0}_{-1}$$

3) Gamma decay:

- ✓ Gamma rays are emitted due to secondary effects: After the emission of an alpha particle or a beta particle, the nucleus is left behind in excited state due to recoil.
- ✓ The excess of energy is released in the form of gamma rays.
- ✓ Thus, γ-rays arise from energy rearrangements in the nucleus.
- ✓ As γ-rays are short wavelength electromagnetic radiations with no charge and no mass, their emission from a radioactive element does not produce a new element.

Properties of α, β, and γ rays

Properties	α − rays	β − rays	γ − rays
Nature photons	Helium nucleus	Fast moving electrons	Electromagnetic waves
Nature of charge	positive	negative	No charge
Magnitude of charge	$3.2\times10^{-19}C(+2e)$	$1.6\times10^{-19}C(-e)$	Zero
Mass	$6.6\times10^{-27}kg(4m_p)$	$3.1\times10^{-31}kg(m_e)$	Rest mass is zero
Velocity	Between 1.4×10^{7} m/sec to 2.2×10^{7} m/sec	1% to 99% velocity of light	3×10^{8} m/sec.
Effect of electric & magnetic fields	Deflected	Deflected	Not deflected
Range	2.7to 8.62 cm in air or 1/100 mm of Al	5mm of Al or 1mm of lead	30 cm of iron
Penetrating power	Minimum	100 times of α -rays	1000 times of α -rays
Ionizing power ($\alpha > \beta > \gamma$)	Maximum (10,000)	Lesser (100)	Minimum (1)
Spectrum	Line and discrete	Continuous	Line and discrete
Mutual interaction with matter	Produces heat	Produces heat	Produces, photo-electric effect, Compton effect, pair production
Path	Straight	Zig zag	No specific path

⇒ *The decay or activity constant can be defined as:*

$$\lambda = \frac{Decay\ rate}{No\ of\ nucleoids\ before\ decay} = \frac{\Delta N/\Delta t}{N_o}$$

Hence, the ratio of decay rate to the No of nucleoids before decay is called activity constant.

Activity constant only depends upon the initial no of nucleoids before decay.

⇒ Note that Activity constant or rate constant is independent of environmental condition (i.e. temperature, pressure etc.)

⇒ We cannot guess the time of material to be full decayed, so infinite time is required for infinite decay.

Units of Rate of Decay or Activity:

A number of units have been used to express the activity of a radioactive sample. The more commonly used ones are the following:

Curie (Ci):	Becquerel (Bq):	Rutherford (Rd):
The activity of a radioactive sample is said to be one curie when 3.7×10^{10} decays take place per second. Thus; $1Ci = 3.7\times10^{10}\ decays/s$ This is the approximate activity of 1 g of radium. In practice, the smaller units milli curie and micro curie are used. $1mCi = 3.7\times10^{7}\ decays/s$ $1\mu Ci = 3.7\times10^{4}\ decays/s$	The SI unit of activity is called the Becquerel and it represents 1 decay per second. Thus $1\ Bq = 1\ decay/s$ We thus have $1Ci = 3.7\times10^{10}\ Bq$	Another unit for activity is Rutherford and it represents 10^{6} decays per second. $1Rd = 10^{6}\ decays/s$

Radioactive dating

⇒ Sometimes we here from peoples that this fossil is that much years old (i.e. 2000 years old) this is one of the applications of radioactive dating. We check its age through this way.

⇒ The decay rate is given by:

$$\frac{\Delta N}{\Delta t} = \lambda N_o \rightarrow (i)$$

Integrating this equation;

$$\log_e N = -\lambda t + C$$

$$\because at\ t = 0, N = N_o \Rightarrow C = \log_e N$$

$$\Rightarrow \log_e N = -\lambda t + \log_e N_o$$

$$or\ N = N_o e^{-\lambda t} \rightarrow (ii)$$

⇒ Equation (ii) shows that no. of nuclei of given radioactive substance decreases exponentially with time. It also shows that decays occur rapidly initially and rate of decay decreases with time.

Half life ($T_{1/2}$)

⇒ The time in which half of radioactive substance decays is known as half-life.

$$If \rightarrow t = T_{1/2}, N = \frac{N_o}{2}$$

$$\frac{N_o}{2} = N_o e^{-\lambda T_{1/2}} \Rightarrow T_{1/2} = \frac{\log_e 2}{\lambda} = \frac{0.693}{\lambda}$$

⇒ **Special case:**

✓ Number of Nuclei left after n half-lives after time $t = nT_{1/2}$:
If $t = nT_{1/2}$ where n is any integer the equation ($N = N_o e^{-\lambda t}$) can be written as: $N = N_o\left(\frac{1}{2}\right)^n = \frac{N_o}{2^n}$

✓ Or:

$$N_o \xrightarrow[half\ life]{After\ 1^{st}} \frac{N_o}{2} \xrightarrow{2} N_o\left(\frac{1}{2}\right)^2 \xrightarrow{3} N_o\left(\frac{1}{2}\right)^3 \ldots \xrightarrow{n} N_o\left(\frac{1}{2}\right)^n$$

Mean life:

Effect on atomic mass after emission	Decreases by 4	Same	Same
Effect on atomic number after emission	Decreases by 2	Increases by 1	Same

penetration power

$$\text{Peneteration power} \propto \frac{1}{size} (energy = constant)$$

$$\text{Penerteration power} \propto Energy\ (Size = constant)$$

Ionization power

$$\text{Ionization power} \propto Size\ (Energy = constant)$$

$$\text{Ionization power} \propto Energy\ (Size = constant)$$

Important tricks

⇒ **α-particle emission:** When an alpha particle emits the position of daughter element is two places to the left in the periodic table from parent element.

⇒ **β-particle emission:** When an β -particle emits the position of daughter element is one place right in the periodic table from parent element.

No of alpha particles emitted is calculated by;

$$N_\alpha = \frac{A - A'}{4}$$

⇒ **No of beta particles emitted is calculated by;**

$$N_\beta = (2n_\alpha - Z + Z')$$

$$Z \rightarrow At.No\ of\ parent,\quad Z' \rightarrow At.No\ of\ end\ product$$

⇒ **Special case:** If in a radioactive transformation, 1 alpha and 2 beta particles are emitted, the resulting nucleus possesses the same atomic number but atomic mass is less by 4 units. A radioactive transformation of this type always produces an isotope of the parent element.

⇒ The quantum energy of γ-rays emitted by a radioactive substance can have unique and discrete values.

⇒ The energy of α-particles emitted by a radioactive substance (α-emitter) has unique value.

⇒ The energy of β −particles emitted by a radioactive substance, (β-emitter) can have any value between zero and end point energy.

COMMON DEFAULT

? Incorrect: Since β -particles (electrons) are emitted from the nucleus shows that electrons exist in nucleus.

√ Correct: β-particle cannot exist in nucleus. It is created and ejected at once at the time of β -decay. β -particle cannot exist in the nucleus because its wavelength is greater than the size of nucleus.

Law of Radioactive Disintegration (Decay law)

- Radioactivity is a process in which nuclei of certain elements undergo spontaneous disintegration without excitation by any external means.
- The radioactivity results the emission of powerful radiations known as Alpha(α), Beta (β) and Gamma (γ) rays.
- Radioactivity is a nuclear phenomenon i.e. it is not depending upon no. of electrons present in outer shell.
- It was studied by Rutherford and Soddy in 1902. The disintegration of nuclei is purely statistical which means all nuclei take different time to disintegrate and are independent for radioactive decay.
- Rate of disintegration is directly proportional to no. of not decayed nuclei present at that time;

$$\frac{\Delta N}{\Delta t} \propto -N_o (Population\ ratio)$$

$$\frac{\Delta N}{\Delta t} \rightarrow Decay\ rate, Death\ ratio, disintegration\ rate,$$

negative sign shows that no of Nucleoids decreasing

$$\frac{\Delta N}{\Delta t} \propto -N_o \Rightarrow \frac{\Delta N}{\Delta t} = (constant) - N_o \Rightarrow \frac{\Delta N}{\Delta t} - \lambda N_o$$

Where λ is called decay/Activity constant.

- The reciprocal of activity constant is known as mean life.
- The complete definition of mean life is: "it is the average life of radioactive element".

$$T = \frac{1}{\lambda}$$

- ***Relationship between half-life and mean life:***

$$T_{1/2} \frac{\ln_2}{\lambda} \Rightarrow T_{1/2} = T\ln^2 \Rightarrow T_{1/2(\text{half life})} = 0.69\,T_{\text{mean life}}$$

Hence. The half-life is smaller than the mean life by a factor of the natural logarithm of 2.2

Difference between half-life and mean life:

- The half-life (median lifetime) is the time required for ½ of the radioactive atoms to decay. A radioactive half-life of one hour will decay half of its element in one hour. The half-life is necessary for the decay formula.
- The mean life (average lifetime) is the expected life for the radioactive atom within a sample. It is the average of the lifetimes of the individual atoms. For example, "If we took a sample of radioactive atoms and wait for all of them to decay away, and keep track of how long each atom lasts. The sum of all the lifetimes of the atoms, divided by the original number of atoms, is the mean lifetime."
- By chance, there are always a few atoms among a sample that live longer than the usual. These longer living atoms do not affect the median lifetime but pull up the average lifetime. *The shortest life of an atom is zero.* Therefore, atoms cannot lower the average lifetime. Because of this, the average lifetime is longer than the median.

Important Formulae + Tricks

- ***Total time required to decay:***

$$T = hT_{1/2}$$

$T \rightarrow$ total time, $h \rightarrow$ no of half life live, $T_{1/2} \rightarrow$ Time for half life

- ***Fraction of the sample decay after n-half life can be found by:***

$$\frac{2^h - 1}{2^h}$$

- ***Remaining number of nuclei (N)/Instantaneous nuclei can be found by:***

$$N = \frac{N_o}{2^{\text{half life}}}$$

Q: we have radioactive element after 1 half-life its. 1) Total time, 2) fraction decay, 3) fraction un-decay; similarly after 2^{nd}, 3^{rd}, 4^{th} (half-life) and so on its. time, fraction decay, fraction un-decay can be found by using:

Time	$1T_{\frac{1}{2}}$	$2T_{\frac{1}{2}}$	$3T_{\frac{1}{2}}$	$4T_{\frac{1}{2}}$
Fraction decay	$\frac{N_o}{2}$	$\frac{3N_o}{4} \rightarrow \frac{3}{4}$	$\frac{7N_o}{8} \rightarrow \frac{7}{8}$	$\frac{15N_o}{16} \rightarrow \frac{15}{16}$
Fraction undecayed	$\frac{N_o}{2}$	$\frac{N_o}{4} \rightarrow \frac{1}{4}$	$\frac{N_o}{8} \rightarrow \frac{1}{8}$	$\frac{N_o}{16} \rightarrow \frac{1}{16}$
% decay	50%	75%	87.5%	93.75%
% un-decay	50%	25%	12.5%	6.25%

- ***% Fraction un-decay:***

$$\%\,Fraction\ undecay = 100\% - \%\,Fraction\ decay$$

MCQ (6 in 1):

7500 gm of radioactive material decay where mass before decay was 8000 gm when half-life of radioactive material is 2 months then?

✓ **No of half-life lived?**

After 1^{st} half life $\Rightarrow 8000 \rightarrow 4000$
After 2^{nd} half life $\Rightarrow 4000 \rightarrow 2000$
After 3^{rd} half life $\Rightarrow 2000 \rightarrow 1000$
After 2^{nd} half life $\Rightarrow 1000 \rightarrow 500$
$4000 + 2000 + 1000 + 500 = 7500$
So, the total number of half-life's lived are 4.

✓ Total time it takes to decay?

$$T_{total\ time} = N_{half\ life} \times half\ life = 4 \times 2 = 8\ months$$

✓ Fraction decay?

$$\frac{2^n - 1}{2^n} \Rightarrow \frac{2^4 - 1}{2^4} \Rightarrow \frac{15}{16}$$

✓ Fraction un-decay?

$$\frac{1}{2^n} \Rightarrow \frac{1}{2^4} \Rightarrow \frac{1}{16}$$

✓ Percentage decay?

$$\frac{15}{16} \times 100\% = 93.75\%$$

✓ Percentage un-decay?

$$\frac{1}{16} \times 100\% = 6.25\%$$

Radiation detector

⇒ A device used to detect the presence/absence and penetration power of radiation.

⇒ The basic principle on which different radiation detectors works is "ionization power of radiation".

⇒ There are three types of radiation detectors;
- ✓ Geiger muller counter
- ✓ Solid state chamber
- ✓ Wilson cloud chamber

Geiger muller counter

⇒ ***Principle***

Radiation ionizes the gas through which they pass and produces few ions. If the applied voltage is strong enough, these ions produce a secondary avalanche and small voltage drop is recorded across the load. This voltage is amplified so that the counter can record it.

⇒ ***Parts:***

rugged metal cylinder which acts as cathode

wire of tungsten that acts as anode

Cathode and anode are separated by ebonite plugs.

DC battery (1000 – 2000 Volts)

Inert gases like Argon etc. is used

⇒ ***Working:***

A dc potential about 1200 volt is applied between the cathode and anode.

When the radiation enters in the GM tube through the mica window it ionizes few argon atoms.

If the applied voltage is strong enough, these ions produce a secondary avalanche that causes a current pulse.

The current through RL produces a voltage pulse of the order of 10 mV.

This voltage is amplified up to 5 -15 Volt by vacuum tube amplifiers and is then applied to the counter.

As each incoming radiation produces a pulse the number of radiations are counted.

⇒ ***Reading of graph plotted from Geiger muller counter:***

In graph the number of highest peaks always shows alpha rays.

The number of intermediate peaks shows beta rays.

The presence of lowest peak shows gamma rays.

Characteristic of G M Counter

The characteristic shows the plot of count / min as a function of voltage
- ➢ For voltage less than 1000 Volt there is no discharge and hence no counts.
- ➢ Between 1000 – 1200 Volts, the number of counts increases linearly with the applied voltage. The region is called proportional region
- ➢ Above 1200 Volt up to 1500 Volt the count rate shows least variation, almost constant the region is called the plateau region or Geiger region or Operating region.
- ➢ If the voltage is applied above 1500 volt a continuous discharge will take place, count rate increases rapidly due to discharge of Argon gas which is undesirable.

Quenching

It is the process to prevent the continuous discharge. Self-quenching is done by vapors of ethyl alcohol because its ionization energy is less than the ionization energy of Argon atom.

Solid state detector

⇒ Solid state detector is simply a P-N junction diode operating under reverse biased.

⇒ When radiation (α, β, γ) interacts with a P-N junction diode an electron-hole pair is produces which combines with their respective minorities and produces a huge current.

⇒ From the current a waveform is obtained and can be observed through oscilloscope.

⇒ Note that: we prefer solid state detector over Geiger muller counter because;

1) It is fast counter
2) No need of huge information for operating
3) Easy counting
4) Less time consuming
5) No need of quenching
6) Utilize less energy

Nuclear reactions

⇒ The reactions in which nuclei of atoms interact with *other* nuclei or elementary particles such as alpha particle, proton, deuteron, neutron., resulting in the formation of a new nucleus and one or more elementary particles are called nuclear reactions.

⇒ Nuclear reactions are expressed in the *same fashion* as chemical reactions, i.e., reactants on left hand side and the products on right hand side

⇒ In all nuclear reactions,

- ✓ the total number of protons and neutrons are conserved as in chemical reactions,
- ✓ the number of atoms of each element are conserved.
- ✓ Linear and angular momentum are also conserved.
- ✓ Conservation of mass energy is also obeyed.

⇒ Some of the characteristics that *differentiate* between nuclear reactions and ordinary chemical reactions are summarized below;

Nuclear reaction	Chemical reaction
Element may be converted from *one form* to another	No new element can be produced
Particles within the nucleus are involved	Only outermost electrons particulate
Often accompanied by release or absorption of tremendous amount of energy.	Accompanied by release or absorption of relatively small amount of energy.
Rate of reaction is independent of external conditions such as catalysts, pressure etc	Rate of reaction depends upon external conditions.

Types of Nuclear reactions

There are many types of nuclear reactions, but w-r-t to course here we will study only few of them;

1) Nuclear fission reaction
2) Fission chain reactions

Nuclear fission reactions

⇒ **Discoverer:** It was first observed by German Scientist Otto Hahn and Fritz Strassman in 1983.

⇒ **Introduction:** In nuclear fission heavy nucleus splits into two smaller nuclei with liberation of energy. When uranium with Z=92 is bombarded with neutrons, it splits into two fragments namely barium (Z=56) and krypton (Z=36) and a large amount of energy is released which appears due to decrease in the mass.

⇒ **Representation:**

$$U_{92}^{235} + n_0^1 \longrightarrow Ba_{56}^{139} + kr_{36}^{94} + 3n_0^1 + Energy$$

⇒ **Definition:** The disintegration process in which heavy nucleus after capturing a neutron splits up into nuclei of nearly equal mass is called nuclear fission.

⇒ *Energy released in nuclear fission:* The amount of energy released in nuclear fission may be obtained by the method of mass defect.

For Example:

consider the fission of U^{235} (Z=92) into Ba^{141} (Z=56) and Kr^{92} (Z=36) by slow neutron.

The reaction is given by:

$$U^{235}_{92} + n^1_0 \longrightarrow Ba^{139}_{56} + kr^{88}_{36} + 3n^1_0 + Energy$$

Let us estimate the actual masses before and after the fission reactions.

Actual mass before fission reaction:	Actual mass after the fission reaction
Mass of uranium nucleus 235.124 a. m. u Mass of neutron 1.009 a. m. u ∴Total mass 236.133 a. m. u	Mass of barium nucleus 140.958 a. m. u Mass of krypton nucleus 91.926 a. m. u Mass of three neutrons 3.026 a. m. u ∴Total mass 235.910 a. m. u

Now mass decrease during nuclear reaction = 236.133-235.910=0.223 a. m. u

∴ Corresponding energy release =0.223× 931 =200 MeV

If we calculate the energy produced by one gm of uranium it comes out to be

2.28×10^4 k.w.h. = 22.8 M watt.

This shows that 1 kg of U236 would give power of 1 M watt for more than two years.

Important points in Nuclear fission reaction

- ✓ $Z_{fragments} < Z$(parent nucleus released).
- ✓ on average 2 or 3 neutron is released.
- ✓ $\frac{3+2}{2} = 2.5$ on average 2.5 neutrons are produced.
- ✓ large amount of energy released
- ✓ all fragments produced are radioactive.
- ✓ In products it is not sufficient that every time Ba and Kr will be produced.
- ✓ So, the fission of uranium can also give another product.
- ✓ **Induced neutrons:**
  Slow neutron: Low energetic neutrons. U^{235} do fission with slow neutrons.
  Fast neutrons: High energetic neutrons. U^{238} do fission with fast neutrons.
  Slow neutrons are effective then fast.
- ✓ **Product neutrons:**
  Prompt neutrons: the neutron which are produced instantaneously in fission reaction.
  Delayed neutron: the neutrons which are produced after some delay in fission reaction.
  Delay neutron is important/good for fission.
- ✓ **Critical amounts (Mass):** the minimum amounts required to control fission reaction.
  Critical is the minimum amount of mass that is required for a fission reaction to be controlled.

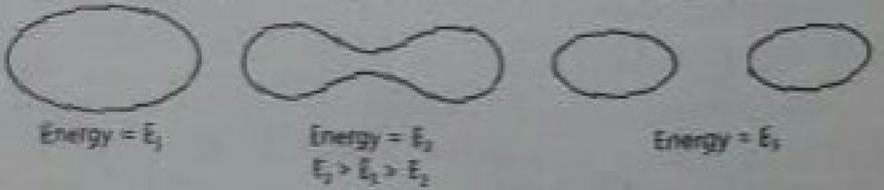
$$if\ m_{fissionable\ fuel} \leq m_{critical} \Rightarrow this\ Rxn\ is\ controlable\ (Used\ nuclear\ reactor)$$
$$if\ m_{fissionable\ fuel} > m_{critical} \Rightarrow Not\ controllable\ (Used\ in\ atomic\ bomb)$$

Applications of nuclear fission: Three practical applications of nuclear fission are:
(a) Atomic bomb, (b) Nuclear reactor and (c) Power plant

Fission chain (Linked) reaction

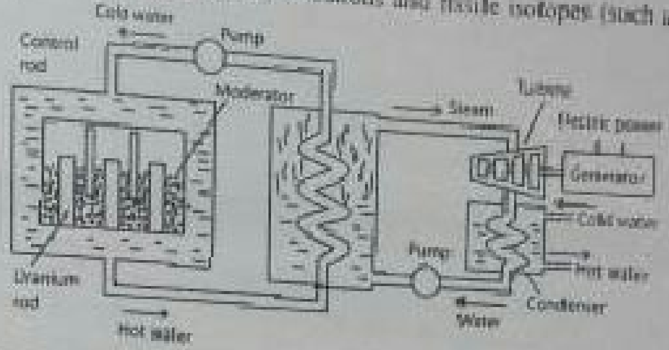
⇒ ***What is chain reaction?***

A nuclear chain reaction occurs when one nuclear reaction causes an average of one or more nuclear reactions, thus leading to a self-propagation series of these reactions. The specific nuclear chain reaction releases several million times more energy per reaction that any chemical reaction.



⇒ ***What is fission chain reaction?***

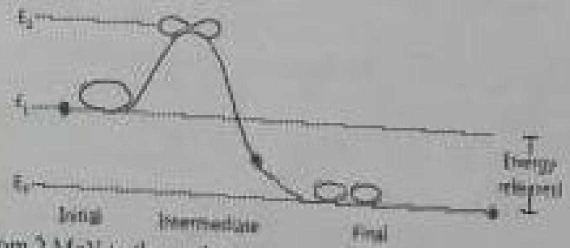
- ✓ Fission chain reaction occurs because of interactions between neutrons and fissile isotopes (such as ^{235}U).
- ✓ The chain reaction requires both the release of neutrons from fissile isotopes undergoing nuclear fission and the subsequent absorption of some of these neutrons in nuclear fission



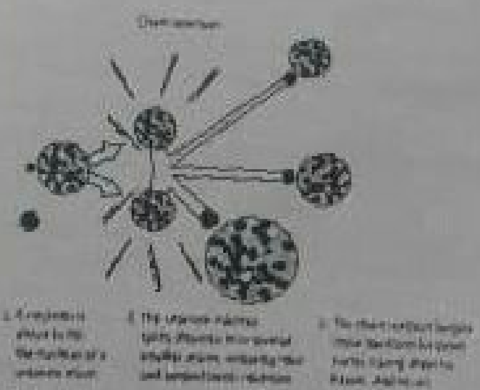
- ✓ A few neutrons (the exact number depends on several factors) are ejected from the reaction.
- ✓ These free neutrons will then interact with the surrounding medium, and if more fissile fuel is present, some may be absorbed and cause more fission. Thus, the cycle repeats to give a reaction that is self-sustaining.

Nuclear reactor

- ⇒ A nuclear reactor is a device to initiate and control a sustained nuclear chain reaction.
- ⇒ Nuclear reactors are used at nuclear power plants for electricity generation and in propulsion of ships.
- ⇒ Heat from nuclear fission is passed to a working fluid (water or gas), which runs through turbines. These either drive a ship's propellers or turn electrical generators. Nuclear generated steam in principle can be used for industrial process heat or for district heating.
- ⇒ Let us see the working of a typical Uranium nuclear reactor. The volume in the core is filled with low-Z material like, D_2O graphite, beryllium etc. This material is called moderator.
- ⇒ When fission takes place in a uranium rod, most of the fast neutrons produced escape from the rod and enter into the moderator.



- ⇒ These neutrons make collisions with the particles of the moderator and thus slow down. About 25 collisions with deuteron (present in heavy water) or 100 collisions with carbon or beryllium are sufficient to slow down a neutron from 2 MeV to thermal energies.
- ⇒ The distances between the rods are adjusted in such a way that a neutron coming from one rod is generally slowed down to thermal energies before entering the other rod. This eliminates the possibility of a neutron being absorbed by U^{238} in 1-100 eV regions.
- ⇒ The geometry of the core is such that out of the average 2.5 neutrons produced per fission, 1 neutron is used to trigger the next fission and the remaining are lost without triggering any fission. The reaction is then sustained at a constant rate.
- ⇒ If the rate of the loss of neutrons is decreased further, the fission rate will keep on increasing which may lead to explosion.



- ⇒ If the rate of loss of neutrons is increased, the rate of fission will keep on decreasing and ultimately the chain reaction will stop.
- ⇒ The finer control of fission rate is made by the control rods which are made of cadmium and are inserted up to a certain depth in the moderator. Cadmium is a very good neutron absorber.
- ⇒ If the stage is set for stable chain reaction and the cadmium rods are pushed into the moderator, the reactor will be shut off.
- ⇒ Pulling the cadmium rods out will start the reactor.

Types of Nuclear reactors

1) Thermal reactors
2) Fast reactors

Why slow neutrons reactors are called thermal reactors?

("Thermal" does not mean hot in an absolute sense, but means in thermal equilibrium with the medium it is interacting with, the reactor's fuel, moderator and structure, which is much lower energy than the fast neutrons initially produced by fission.)

Thermal reactors	Fast reactors
Make use of slow neutrons. i.e. U^{235}	Make use of fast neutrons. i.e. U^{238}
Slow neutrons are more easily caught, so that was the first kind of reactor made.	Fast neutron reactors need much more enriched fissionable materials.

Nuclear Fusion reaction

⇒ *Definition:* A nuclear reaction in which two lighter nuclei are fused together to form a heavier nucleus is called nuclear fusion.

⇒ When lighter nuclei with A<20 combine to form bigger nuclei binding energy per nucleon increases. The total binding energy of the product is less than total binding energy of reactants resulting in release of energy. This process of combining of two lighter nuclei into bigger one is known as nuclear fusion.

⇒ A fusion reaction is difficult to occur because positively charged nuclei repel each other. At very high temperatures of the order of 10^6 to 10^7 K. The nuclei may have sufficient energy to overcome the repulsive forces and fuse.

⇒ It is for this reason; fusion reactions are also called thermonuclear reactions.

⇒ Fusion reactions are highly exothermic in nature because loss of mass occurs when heavier nuclei are formed from the two lighter nuclei. To initiate a fusion reaction is difficult, but once it is started, its continuity is maintained due to huge release of energy.

⇒ Some examples of the fusion reactions are given below;

$$H_1^2 + H_1^2 \longrightarrow He_2^4 + 24\ Mev$$
$$H_1^3 + H_1^3 \longrightarrow He_2^4 + 2n_0^1 + 11.0\ Mev$$
$$H_1^1 + H_1^3 \longrightarrow He_2^4 + 20.0\ Mev$$
$$H_1^2 + H_1^3 \longrightarrow He_2^4 + n_0^1 + 17.8\ Mev$$
$$Li_3^7 + H_1^1 \longrightarrow 2He_2^4 + 17.7\ Mev$$

⇒ Hydrogen bomb is based on fusion reactions. Energy released is so enormous that it is about 1000 times that of an atomic bomb.

⇒ In hydrogen bomb, a mixture of deuterium oxide (D_2O) and tritium oxide (T_2O) is enclosed in a space surrounding an ordinary atomic bomb.

⇒ The temperature produced by the explosion of the atomic bomb initiates the fusion reaction between H_1^3 and H_1^2 releasing huge amount of energy.

⇒ The first hydrogen bomb was exploded in 1952. So far, it has not been possible to bring about fusion under controlled conditions.

⇒ It is believed that the high temperature of stars including the sun is due to fusion reactions.

⇒ Bethe and Weizsacker, in 1939, proposed that a carbon-nitrogen cycle is responsible for the production of solar energy in which hydrogen is converted into helium. Here C_6^{12} is a nuclear catalyst.

⇒ As a potential source of commercial electrical power, the fusion process has several advantages over the fission reaction.

(i) The quantity of energy liberated in the fusion is much greater than in fission.

(ii) The products of fusion are non-radioactive.

⇒ Fission produces many unstable radioactive products.

⇒ Fission reactors, therefore, pose a waste-disposal problem.

Difference between Nuclear Fission and Nuclear Fusion

Nuclear Fission	Nuclear Fusion

Chapter No: 20 "Nuclear Physics"

If two current carrying parallel conductors are placed near each other, then force (repulsive or attractive) acts on them. This is the electromagnetic force. If the conductors carry, currents in the same direction, then they attract each other i.e., electromagnetic force is attractive. If the conductors carry currents in the opposite direction, then they repel each other.

i. In atoms, the electrons are bound by the electromagnetic forces acting on them due to protons.
ii. Atoms combine to form molecules due to electromagnetic forces.

3) The strong nuclear force:

The strong nuclear force is the attractive force that holds the constituents of the atomic nucleus viz., protons and neutrons. The stability of the nucleus suggest that attractive nuclear forces must be very strong. For example, consider the helium nucleus ($_2He^4$ consisting of two protons and two neutrons and contained in a volume with a radius of about 10^{-15}m. The protons are so close together that repulsive electric force is very large. The gravitational force between them is negligible yet $_2He^4$ is very stable. It is because the strong attractive nuclear force acting between all the constituents of the nucleus overpowers the repulsive electric force between protons.

Properties:

- ✓ it is basically an attractive force.
- ✓ It is a short-range force and operates only up-to distances of the order of 10^{-14}m.
- ✓ it does not depend upon the charge on the nucleons.
- ✓ It is a non-central force.
- ✓ It does not obey inverse square law.
- ✓ It is a non –conservative force.

Example:

i. It is the strong nuclear force that binds the neutrons and protons together in a nucleus.
ii. The nuclear energy available from the processes of nuclear fission and fusion uses the concept of strong nuclear force.

4) The weak nuclear force:

The weak nuclear force appears only in certain nuclear processes such as β-decay Of a nucleus. In β-decay, electrons are emitted from a radioactive nucleus. The weak nuclear force is much stronger than the gravitational force.

Building blocks of matter

⇒ Matter is made up of atoms and atoms are made up of electron, proton and neutron.
⇒ Matter is consisting of many particles. More than 100 particles are discovered.
⇒ Now we are going to detailed view of some of the particles from which matter is made up of;

1) Elementary particle:

Those particles which are not composed of other particles.
Electron ad quarks are elementary particles because they are not made up of other particles.

2) Composite:

Those particles which are made up of other particles.
Atoms, proton and neutrons are composite particles because they are made up of other particles.

Types of particles:

I. **Photon:** light particle or packet of energy.
II. **Lepton:** particle which not experience strong nuclear force. E.g. electron and neutrino
III. **Hadrons:** particle which experience strong nuclear force. E.g. Proton and neutron

Types:

Mesons: particles which are lighter than proton.
Formed from quarks and Anti-quarks.

Baryons: particles whose mass is equal or grater than that of proton.
Formed from quarks

1 proton is made of	Made up of 3 quarks ⇒ 2 up (+2/3e) and one down (-1/3e) quark So;

Occurs in heavy nuclei.	Occurs in lighter nuclei.
The heavy nucleus splits into lighter nuclei of comparable masses.	The lighter nuclei fuse together to form a heavy nucleus.
Binding energy per nucleon increases	Binding energy per nucleon decreases.
Reaction can occur at ordinary temperature.	Occurs at very high temperature.
Energy liberated in one fission reaction is 200 MeV.	Energy liberated in one fusion reaction is 24 MeV.
Can be controlled.	Cannot be controlled.
Products are usually unstable and radioactive.	Products are usually stable and non-radioactive.
Links of fission reaction are neutrons.	Links of fission reactions are protons.
Percentage efficiency is less.	Percentage efficiency is high.

Basic forces in nature

There are four basic forces that operate in nature. These are;

1. The gravitational force
2. The electromagnetic force
3. The strong nuclear force
4. The weak nuclear force

1) The gravitational force:

All objects exert a force of attraction upon each other. The gravitational force of attraction between two objects is governed by Newton's law of gravitation. If two objects of masses m1 and m2 are held at a distance r, then according to Newton's law of gravitation, the force of attraction between the two objects is given by

$$F = G\frac{m_1 m_2}{r^2}$$

where G (=6.67 x 10^{-11} $Nm^2 kg^{-2}$) is called universal gravitational constant.

Properties:

- ✓ Always attractive.
- ✓ Unlike electrostatic force which can be attractive or repulsive. It is because mass is of one kind whereas Charge is 0f two kinds (positive and negative).
- ✓ It is a central force i.e., gravitational force between two objects acts along the line joining the centers of the objects.
- ✓ It obeys inverse square law i.e., gravitational force between two object is inversely proportional to the square of distance between them.
- ✓ Of all the four forces operating in nature, the gravitational force is the Weakest.
- ✓ It is a long-range force i.e., it operates over very long distances.
- ✓ It is a conservative force i.e., work done by the gravitational force is recoverable.

Examples:

1. A stone dropped from a height fails because earth exerts gravitational force 0n the stone.
2. The rotation of earth around the sun is due to gravitational pull of sun on earth
3. The moon revolves around the earth due to the gravitational force on it by the earth.

2) The electromagnetic force:

The electromagnetic force includes both electric and magnetic force and is relatively strong.

(a) The force between two static (at rest) electric charges is given by Coulomb's law in electrostatics. If two charges q1 and q2 are at a distance r apart, then according to Coulomb's law, the electrostatic force between them is given by;

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}$$

where ϵ_0 (= 8.854X10^{-12} $C^2N^{-1}m^{-2}$) is called absolute permittivity of free space.

(b) A static charge does not produce magnetic field. However, a moving charge produces magnetic field. When two charges are in motion, each charge experiences a force called electromagnetic force.

Properties:

- ✓ It may be attractive or repulsive. It is because electric charges are of two kinds (positive and negative).
- ✓ It is a central force.
- ✓ It obeys inverse square' law.
- ✓ It is also a long-range force.
- ✓ It is also a conservative force.
- ✓ It is about 10^{36} times stronger than the gravitational force

Examples:

Some important points and tricks

1) Hydrogen nucleus does not require nuclear force for its existence.
2) Hydrogen has three isotopes.
3) No radioactive substance emits both the a and (3 particles simultaneously. The γ-rays are emitted after the emission of the α or β-particles.
4) Atomic clock produces an error of approximately 1 second in 30 years.
5) Half-life period of a substance does not depend on pressure, temperature, density or volume.
6) Half-life period of lead is infinite.
7) Lead is the heaviest stable nucleus.
8) All naturally occurring radioactive substances are ultimately converted into lead.
9) The radioactive substances are stored in lead containers because lead absorbs the radioactive radiations.
10) A neutron can be added to or taken out of the nucleus of an atom without changing its chemical properties.
11) When an electron de-excites to the lower states, a photon is emitted.
12) An atom tends to return to a lower energy state from higher energy state within a time interval of 10 ns.
13) β-decay produces isobars.
14) The β-particles come from within the nuclei.
15) The binding energy of nucleus is equivalent to that of mass defect.
16) In the nuclear reactions, mass and energy are conserved.
17) Thermal neutrons have kinetic energy of the order of other gas molecules in their surroundings.
18) An enriched uranium is that in which the percentage of U-235 in more than 0.7 %.
19) An enriched uranium is a better fuel for the reactor because it has greater proportion of U-235.
20) The moderator of the nuclear reactor should slow down the neutrons without absorbing them.
21) Critical mass of fissionable uranium-235 can be reduced by surrounding it with neutron reflecting substances.
22) In the sun and stars, the energy is released through natural fusion of hydrogen into helium with carbon serving as nuclear catalyst. This carbon cycle was proposed by Bethe.
23) Out of electron, proton and neutron, only neutron is unstable in free space. It decays into a proton and an electron. As a free particle, it has half-life of about 14 minutes.
24) The nuclear force between nucleons having parallel spin is greater than those having antiparallel spins.
25) The decay of artificial radioactive isotopes is accompanied by positron decay.
26) To produce an electron-positron pair, the energy of the γ-particle should be more than 1.02 MeV.
27) The percentage of mass which changes into energy during fission is of the order of 0.7 %.
28) In the fission of uranium, the percentage of mass converted into energy is about 0.1 %.

	$+\frac{2}{3}e+\frac{2}{3}e-\frac{1}{3}e=\frac{4}{3}e-\frac{1}{3}e=\frac{3}{3}e=+e$ That's why charge on proton is positive
1 neutron is made of	Made up of 2 down and one up quarks. $-\frac{1}{3}e-\frac{1}{3}e+\frac{2}{3}e=-\frac{2}{3}e+\frac{2}{3}e=0$

FORMULAS SHEET

1.	Neutron number	$N = A - Z$
2.	Mass spectrograph	$m = \left(\frac{er^2}{2V}\right)B^2$
3.	Mass defect	$\Delta m = (m_p + m_n) - m_{nucleus}$
4.	Mass defect per nucleon	$\frac{\Delta m}{A} = \frac{(m_p + m_n) - m_{nucleus}}{A}$
5.	Binding energy	$B.E = \Delta mc^2 = (m_p + m_n)_Z\, m_{nucleus}\, c^2$
6.	Binding energy per nucleon	$\frac{B.E}{A} = \frac{\Delta mc^2}{A} = \frac{(m_p + m_n) - m_{nucleus}\, c^2}{A}$
7.	Relationship between unified mass scale and energy	$1U = 931\ MeV$
8.	Alpha decay	$X_Z^A \quad Y_{Z-2}^{A-4} + He_2^4$
9.	Beta decay	$X_Z^A \quad Y_{Z+1}^A + e_{-1}^0$
10.	Gamma decay	$X_Z^A \quad X_Z^A + \gamma$ radiation
11.	Decay constant	$\frac{\Delta N}{N} = -\lambda\Delta t$
12.	Half life	$= \left(\frac{1}{2}\right)^n N_o$
13.	No of undecayed atoms	$E_n = -\left(\frac{2\pi^2k^2me^4}{h^2}\right)\frac{1}{n^2} \rightarrow E_n = -\frac{E_o}{n^2} \rightarrow -\frac{13.6}{n^2}\ eV$

UNITS

1.	Decay constant	s^{-1}
2.	Half life	second
3.	Units of radioactivity	curie, bequrrel